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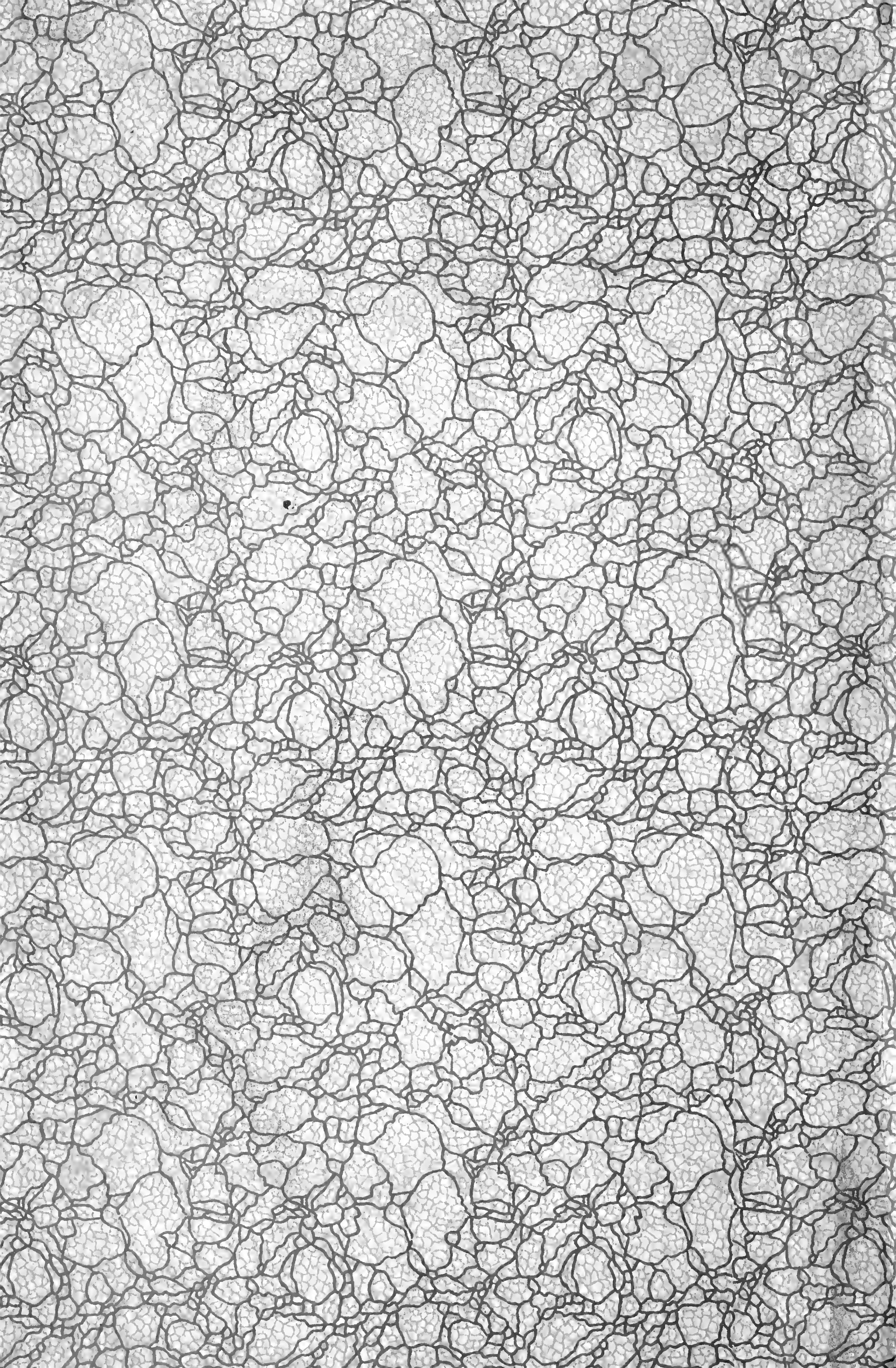

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S. W. STRATTON, DIRECTOR

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LUMINOUS EFFICIENCY OF THE FIREFLY.

By H. E. Ives and W. W. Coblentz.

In connection with an investigation of various sources of illumination, it was deemed of scientific interest to examine the light emitted by the common firefly. It has been an open question whether the narrowness of the spectrum of the firefly is due to its low intensity (i. e., whether the spectral energy extends into the infra-red) or whether the light emitted consists of only a narrow yellowish green band which terminates abruptly in the red and in the blue.

About twenty years ago, Langley and Very [1] made a photometric and bolometric study of one species of firefly, "Pyrophorus Noctilucus," found in Cuba. They found that the radiation of this insect consisted of a band in the yellow-green of the spectrum, which decreased rapidly in intensity toward the red and the blue. The spectrophotometric work was confessedly unsatisfactory, being done visually and hence hindered by the unsteady character of the light, as well as by its low intensity. The authors satisfied themselves that the spectrum, as compared with sunlight, was shorter, not extending far into the blue, or beyond the red, and that its maximum lay at 0.57μ. The accuracy of the visual work was not sufficient, because of the difficulties encountered, to draw an accurate energy curve, or to detect minute spectral structure if it existed. Because of the small amount of energy and of its unsteady character, direct determination of the energy in the visible spectrum by bolometric means was hopeless.

[1] Langley and Very: "The Cheapest Form of Light." Amer. Jour. Sci., 3d ser., vol. 11; 1890. Reprinted in Smithsonian Misc. Coll. No. 1258; 1901.

In 1902 (see Annals Astrophys. Obs., Vol. 2, p. 5) further experiments were made on the relative amount of heat and light in the radiation of the Cuban firefly. No heating whatever could be detected by the bolometer. "A portion of the flame of a standard sperm candle, equal in area to the bright part of the insect, gave, under the same circumstances, a bolometric effect of such magnitude that had the heat of the insect been $\frac{1}{80000}$ as great as this from the candle, it would certainly have been recognized." The candlepower of the insect was $\frac{1}{1600}$ candle.

I. THE QUALITY OF THE LIGHT EMITTED BY THE FIREFLY.

In the present investigation an attempt was made to secure a more exact idea of the energy distribution in the firefly light in the visible spectrum by means not available to the previous investigators. In place of visual observations use was made of photographic plates sensitive to the whole visible spectrum. The following considerations lead to the use of photography. With a radiation meter it is possible to measure radiant energy in the visible spectrum directly, provided the source measured is steady and has sufficient energy to affect the instrument. The energy must be considerable, since instruments of this kind are many thousand times less sensitive than the eye or photographic plate for radiation less than 0.65μ in wave length. With the spectrophotometer it is possible to measure the distribution of visible radiant energy, even if of low intensity, indirectly, by comparing the source with one of known energy distribution, provided again the source measured is steady. If the source measured is unsteady as well as weak neither method of measurement is applicable. For cases of this kind the photographic plate as a record of incident energy is the only resort. Its great advantages are, first, that all portions of the spectrum are recorded simultaneously, so that unsteadiness of total light is no disadvantage; second, the action of the plate is integrative, and therefore the obstacles imposed by low intensity may be overcome by long exposure. A further advantage for the present purpose is that the plates used, Wratten and Wainwright "Panchromatic," are sensitive to all colors of the spectrum and therefore record the whole spectral extent of the firefly light (if limited as indicated by Langley's work).

The apparatus consisted of a large prism spectrograph having a dispersion in the yellow sufficient to separate the yellow mercury lines by about half a millimeter, and giving a spectrum of about seven centimeters length in the visible. A helium tube and a carbon glowlamp, which was carefully calibrated for watts per candle, served for comparison sources, the one for a wave-length scale, the other as a standard of energy distribution.

The fireflies were of the species common in Washington early in July, "Photinus Pyralis." These are much smaller than the West Indian genus, averaging about 12 to 15 mm in length, of which length only about one-half is luminous. The light ordinarily consists of a faint glow, which at periods of a few seconds flashes out with greatly increased intensity. Under the microscope the light-giving portion is seen, when not giving out the bright flash, to be made up of numerous small irregularly scintillating points, reminding one of the spinthariscope. It was at first attempted to secure sufficient light by inclosing a number of the insects in a small cage with a white wall from which the light would be reflected into the slit. It was found, however, that the fireflies in captivity quickly lost their desire to flash, and this scheme was abandoned. The only satisfactory method proved to be to hold the insects in the fingers, one or two at a time over the spectroscope slit. The best specimens would flash as frequently as every three seconds until tired, when others would be substituted for them. Others, after a period of flashing, would yield a steady glow of considerable intensity. With a fairly wide slit, and taking the fireflies as they came, from two to six hours were required to obtain a satisfactory photograph. The work was done evenings and extended over about two weeks before three satisfactory negatives were obtained, one of long exposure, one of short, and one (short exposure) with a very narrow slit. The latter was taken with a view of detecting any irregular structure.

In Fig. 1 is reproduced the long exposure, together with the spectrum of the carbon glowlamp and of the helium tube. The firefly light is confined to a band in the yellow green, ending in the blue green on one side, in the red on the other. The limit on the red side is so far from the limit of sensitiveness of the plates as to leave no doubt that the firefly's spectrum does end within the

limits of the visible spectrum. Langley concluded from his bolometric work that there is no emission of energy in the infra-red. If this is true the complete energy curve may be obtained from the energy emitted in the visible spectrum. From the exposure made with a very narrow slit there is no evidence of fluted or other irregular structure.

The distribution of energy was obtained by measurements of the density of the photographic plates. As is well known, the relation between exposure and density is not the same for all exposures. For a limited range density is proportional to exposure, beyond this range saturation sets in, still farther away reversal, It is therefore necessary to know accurately the exposure equivalent of each density on the plate measured; in other words, to know the "characteristic curve." With this end in view a series of exposures of known relationship were made on the carbon glow lamp, in which the densities covered practically the whole range of those in the best two firefly negatives. All the negatives, it should be noted, were developed under identical conditions, by time, in complete darkness, and should therefore be as nearly comparable as possible without all the exposures in question being made on one plate. The densities of all negatives were measured by means of a Martens polarization photometer, mounted on a dividing engine, in such manner that strips 1 mm wide and 1 mm apart were compared for blackness against the clear unexposed plate. One of the helium lines served as reference mark, and the points of measurement were the same on all plates.

From these observations density curves were plotted as shown in Fig. 2, where the glow lamp curves correspond to exposures of 2, 4, 6, 8, 12, 20, 30, 60, 120, and 240 units; the two firefly curves represent a very long exposure, giving the limits of the spectrum, and a short exposure giving the maximum of the insect's light. Where the firefly exposure curves cross the glowlamp exposure curves the corresponding exposure units may be read off directly. For other points the characteristic curve must be drawn from the glowlamp points, and the firefly value determined by interpolation on the curve. By this procedure the unequal sensitiveness of the plates for different wave lengths is taken care of, and also any change in the density-exposure relationship for different colors.

Fig. 1.

A. Spectrum of "4 watt" carbon glow lamp.
B. Spectrum of fire-fly, "Photinus pyralis."
C. Helium vacuum tube spectrum.

Fig. 6.

From the longest firefly exposure a set of points were so determined for the fainter portions of the energy curve; the stronger portions lay beyond any of the comparison exposure curves, in the

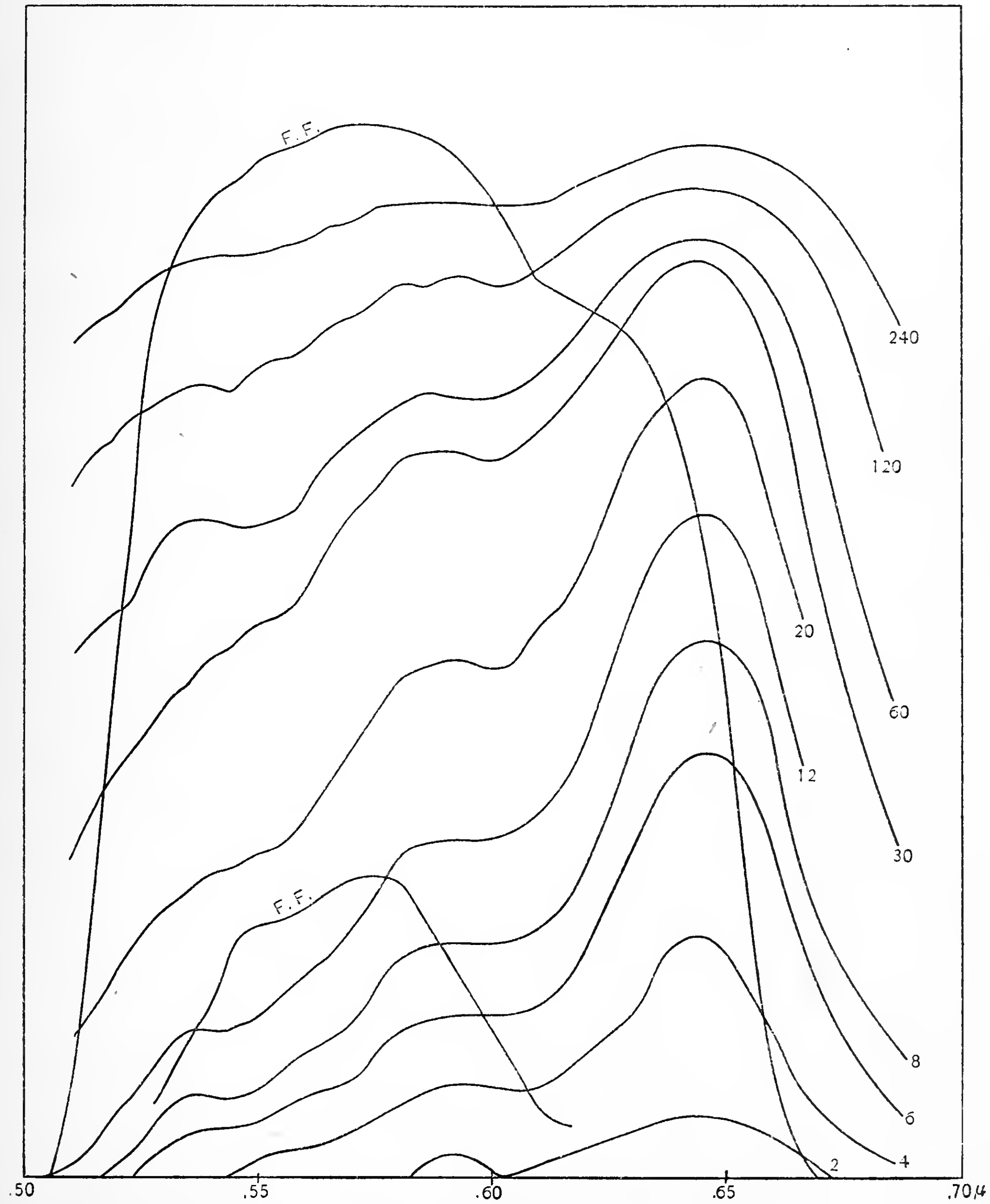

Fig. 2.—Density curves of photographic plates of firefly (F. F.) and glow lamp.

region of saturation, and were therefore unsuitable for measurement. From the short exposure, in which the densities were all below the region of saturation, the intermediate points of the

curve were determined. The two curves overlapped for a short range, from which the multiplying factor to bring them to a common unit was determined. From the values so obtained the ratio $\frac{\text{firefly light}}{\text{glowlamp light}}$ was derived for each point of density measurement. That is, there was obtained the spectrophotometric relationship between the two. The numerical values are given in Table I, column 5.

At this stage it becomes necessary to know the energy distribution of the carbon glowlamp. This can be obtained directly by radiometric methods, the source having the qualities both of steadiness and comparatively large amount of energy.

The spectrophotometric measurements of the complete energy distribution of the carbon glowlamp employed were made by two methods (the one suited best for the longer wave lengths, the other for the shorter), which gave very concordant results over their common range. In the first method an improved and highly sensitive bolometer, a fluorite prism, and mirror spectrometer[2] were employed to obtain the spectral distribution of energy from 0.55μ to 4μ in the infra red, where the glass walls of the lamp become opaque. The numerical values of the spectral intensities as obtained by this method are given in Table I, column 3. The lamp (a 110-volt, 16-candlepower, 4 watts per mean horizontal candle, treated carbon filament) was operated at a fixed voltage corresponding, as determined by careful calibration, to 3.99 watts per mean horizontal candle. For the type of filament (oval anchored) this means 4.83 watts per mean spherical candle, or 2.60 lumens per watt. The unit of candlepower is the new International Candle, 1.6 per cent lower than the unit as hitherto maintained at the Bureau of Standards. The black body temperature for red light ($\lambda = 0.66\mu$) as observed with an optical pyrometer was $1790° \pm 20°$ C. The wave length of maximum energy is $\lambda_{max} = 1.41\mu$; the computed radiation constant is $\alpha = 5.7$, which means that the emissivity of this treated filament is of the order of ($\alpha - 1 =$) 4.7th power of the absolute temperature. The observations were corrected for the variation in the reflecting

[2] For adjustment of apparatus, lamp, computations of radiation constants, etc., see papers by Coblentz, this Bulletin, **4**, p. 391; **5**, p. 339.

power of the silvered mirrors of the spectrometer (data from Hagen and Rubens) on the assumption that the mirrors were perfectly new, which was not the case. Hence the observations are to some extent undercorrected toward the violet.

TABLE I.

Emissivity of Carbon Glowlamp			λ	Firefly / Glowlamp	Firefly energy distribution
λ	Glass Prism	Fluorite Prism			
0.50μ	3.9	. . .	0.500μ	0	0
.52	5.5	2.6	.512	.65	.03
.54	7.5	. . .	.517	1.0	.05
.56	10.0	5.1	.521	2.0	.10
.58	12.9	. . .	.526	4.0	.22
.60	16.1	8.2	.531	8.9	.53
.62	20.1	10.1	.537	12.0	.79
.64	24.8	. . .	.545	16.0	1.15
.65	27.3	13.6	.550	16.3	1.26
.66	29.7	14.9	.555	16.0	1.31
.68	35.3	. . .	.560	15.5	1.365
.70	41.5	20.8	.565	15.1	1.40
.8		39.1	.575	13.0	1.40
.9		57.9	.578	12.0	1.35
1.0		73.4	.580	10.7	1.26
1.1		88.8	.586	9.0	1.095
1.2		100.5	.589	8.0	1.02
1.3		106.2	.598	6.0	.86
1.4		107.6	.608	4.0	.62
1.5		107.0	.621	2.0	.355
1.6		104.5	.627	1.0	.19
1.8		95.1	.637	.65	.135
2.0		82.8	.643	.4	.09
2.2		69.4	.647	.26	.06
2.4		56.0	.652	.20	.05
2.6		42.5	.659	.13	.035
2.8		30.6	.665	.06	.015
3.0		23.5	.670	0	0
3.5		12.5			
4.0		5.4			
4.5		.12			

The second method of measuring the distribution of energy (in the visible spectrum) was by means of a Rubens thermopile and a Fuess two-prism monochromatic illuminator, in which the lenses had a focal length of only about 10 cm. This gave a more intense spectrum and at the same time a larger dispersion than obtained in the preceding apparatus. This combination also eliminated the question of the reflecting power of the mirrors, which is difficult to determine in the visible spectrum. The numerical values are given in the second column of Table I. The complete energy curve, Fig. 3, was made by combining the two sets of observations

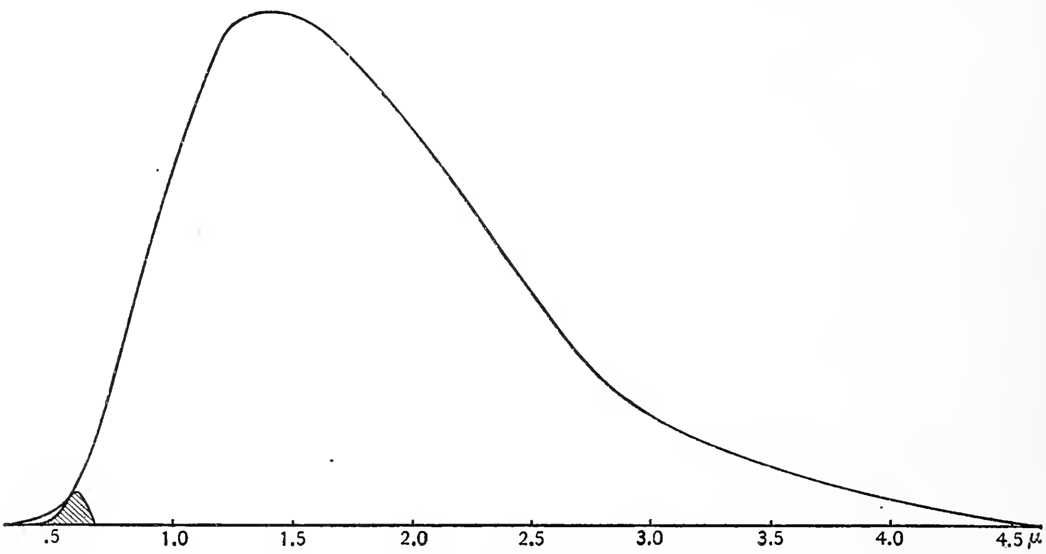

Fig. 3.—Luminous efficiency of the 4-watt carbon glow lamp. (Shaded area ÷ total area.)

reduced to equality at 0.6μ. The two curves so obtained agreed over their common range as closely as one would expect, considering the difficulties in obtaining such measurements.

Having already obtained the spectrophotometric relationship between the firefly and the glowlamp (by photographic means) and now knowing the distribution of energy of the glowlamp, we can at once obtain the distribution of energy in the spectrum of the firefly by multiplying the energy values of the glowlamp by the ratio $\frac{\text{firefly light}}{\text{glowlamp light}}$ at each wave length. In Fig. 4 are given the two curves—the energy of the glowlamp in the visible spectrum, and the energy of the firefly. The points on the latter are

obtained by comparison with the smoothed curve of the glow-lamp; equality is assumed at 0.59μ. In Table I, column 6, are given the energy values so derived at wave lengths corresponding

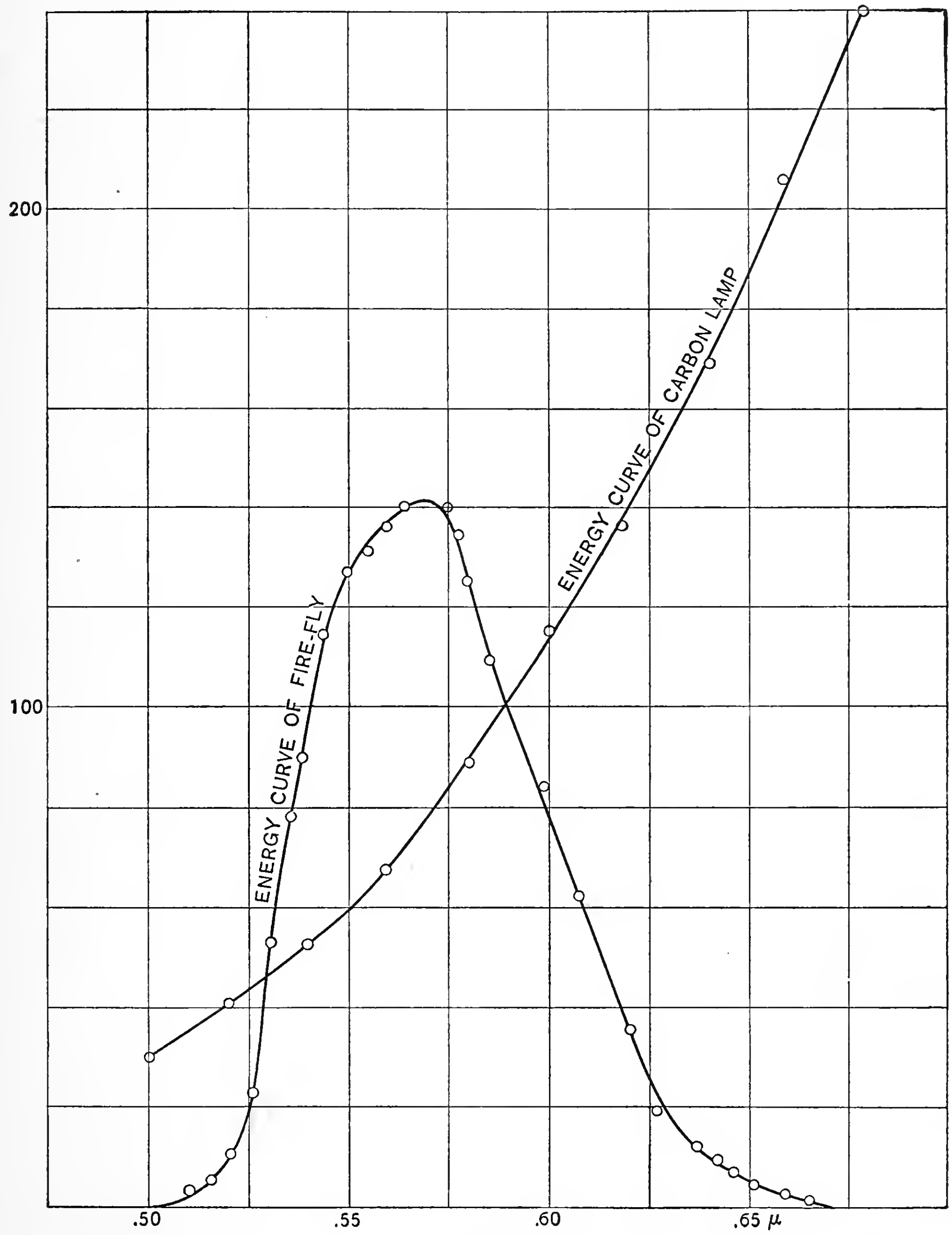

Fig. 4.

either to points of density measurement or to points of intersection of density curves, as explained above.

It will be seen that the maximum of light emission is in the part of the spectrum to which the eye is most sensitive, the yellow

green, at 0.57μ, and the extent of the spectrum is from 0.50μ to 0.67μ. Very much longer exposure might have shown greater length. It must be borne in mind that the measurements were made on extremely small areas, subject to errors from such local unevennesses in the plates as might occur[3] and therefore it is believed no particular significance is to be attached to the apparent slight concavity on the red side of the maximum or the twisted appearance of the maximum itself. The greater extension on the red side makes it similar in appearance to the complete radiator. Since the distribution of energy in the spectrum of the sun is approximately uniform through this region, the spectrum of the firefly as compared with sunlight has very closely the same character as the energy curve shown.

It is of interest to compare the luminous efficiency of the firefly with that of the carbon glow lamp, and indirectly, with that of other luminants. If we know the relative visual intensity values of the different colors of the spectrum of a source of known energy distribution (the sensibility curve of the eye if the source gives a normal or equal energy spectrum) we can calculate the intensity value of any given energy distribution, and from it obtain the ratio $\frac{\text{light (radiated energy} \times \text{visual sensibility)}}{\text{radiated energy}}$ in common units. Koenig has determined the intensity distribution of a gas flame, and from the energy distribution of the flame as determined by Langley, Koenig's observations are expressible in terms of a spectrum of uniform energy distribution. These are given by Nutting[4] and the values for intensities above the Purkinje effect are here used.[5] The procedure is to multiply the energy at each point by the fraction representing its visual intensity value. In Fig. 3

[3] A defect in the plate made it necessary to omit a density measurement at 0.57μ.

[4] This Bulletin, **5**, p. 261. The value unity is given to the maximum of intensity (.565μ).

[5] These intensity values are of course dependent on the accuracy of the gas flame energy values. These are much lower in the blue than for the glow lamp here used, which would suggest, since a gas flame is rather bluer than the 4-watt lamp, that a redetermination of the quantities in question by more sensitive means would change the intensity values used. The effect on the final values for luminous efficiency in this paper would not be altered appreciably by changes of the extent indicated by this apparent discrepancy.

this is done for the glowlamp and in Fig. 5 for the firefly. The shaded area in each case represents the energy available as light expressed photometrically or in terms of intensity. The ratio of

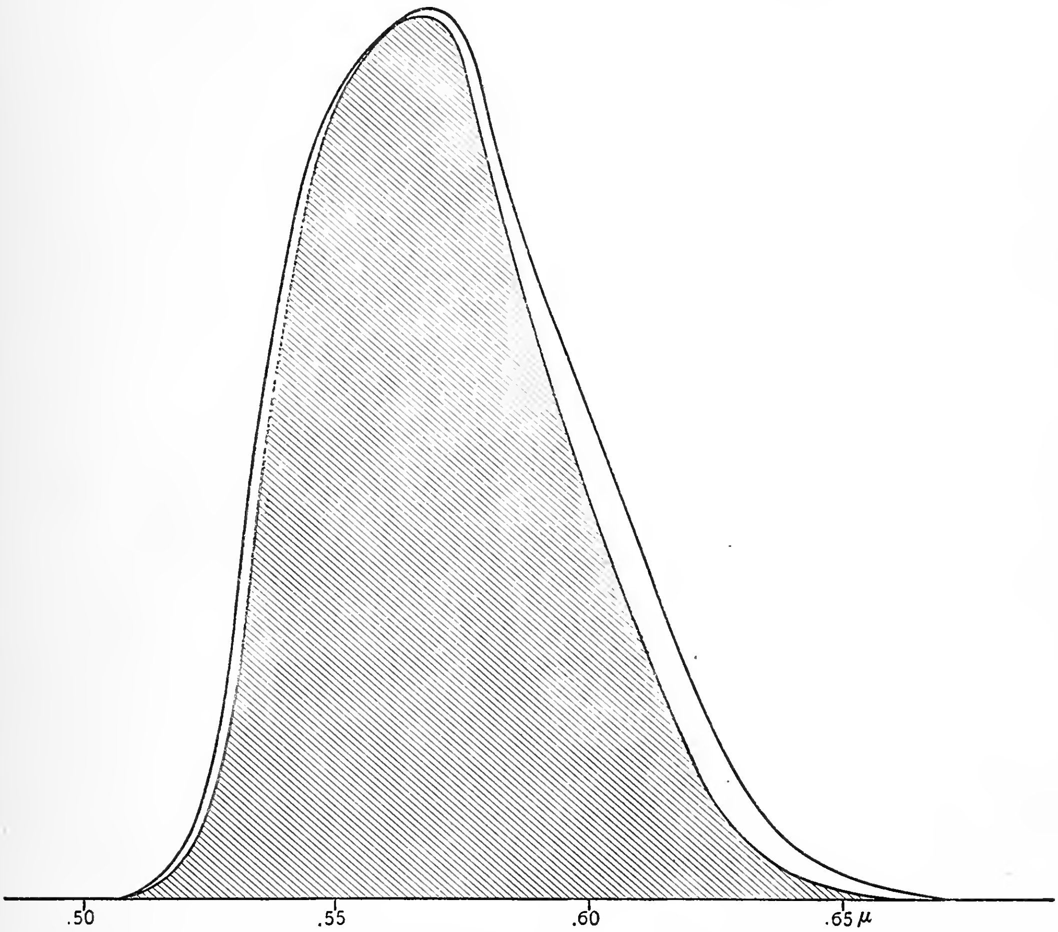

Fig. 5.—Luminous efficiency of the firefly. (Shaded area to total area.)

the shaded to the whole area gives the luminous efficiency, that is

$$\frac{\text{light (radiated energy} \times \text{visual sensibility)}^{6}}{\text{total radiated energy.}}$$

For the glowlamp it is 0.43 per cent; for the firefly 96.5 per cent, these numbers representing the relative amounts of light (measured on a photometer) for equal amounts of radiated energy—a

[6] This method of calculating luminous efficiency was first suggested, it is believed, by C. E. Guillaume (Soc. Int. Elect. Bull., **5**, pp. 396–400; May, 1905). The numerical values are not to be compared with those obtained from the older method of calculating this quantity, in which the ratio of radiated energy between 0.38μ and 0.76μ to the total radiation is sought, a quantity having no direct relationship with efficiency as ordinarily understood in connection with artificial illuminants.

striking illustration of the wastefulness of artificial methods of light production. From the specific consumption of the tungsten lamp (1.6 w. p. s. c.) and the mercury arc (0.55 w. p. s. c.) we obtain by comparison with the carbon filament that their luminous efficiencies are 1.3 per cent and 3.8 per cent. The most efficient artificial illuminant therefore has about 4 per cent of the luminous efficiency of the firefly.

We may express these comparisons in a different way if we make one assumption. Let us assume all the applied energy in the glowlamp to be used in producing radiation, none being lost by convection or conduction in the evacuated bulb, base connections, and glass walls. The glowlamp has an efficiency of 4.83 watts per mean spherical candle, so we may say the firefly has an efficiency of .02 watts per candle, a quantity, because of our assumption, representing the upper limit of the specific consumption. This is to be compared with the tungsten lamp at 1.6 watts per candle and the mercury arc at 0.55 watts per candle.

These figures are, however, to a certain extent misleading, for they give no weight to the question of color. The light of the firefly would not be acceptable as an illuminant for general purposes because of its green hue and small spectral extent. The color values of objects illuminated by it would be distorted to a greater extent than by the mercury arc. All hues would be submerged in a nearly uniform green. Considered from the point of view of the amount of white sensation as compared with the total luminous sensation [7] the firefly is very inefficient. This is of course a necessary consequence of the relationship between color and visual intensity, the most efficient light—disregarding the requirements of color—would be a single spectral line in the green. Its luminous efficiency, on the basis used above, would be 100 per cent, but it would be quite unsuitable for ordinary illumination. We may say, therefore, that the firefly has carried the striving for efficiency too far to be acceptable to human use; it has produced the most efficient light known, as far as amount of light for expenditure of energy is concerned, but has produced it at the (inevitable) expense of range of color. The most efficient

[7] H. E. Ives, Illuminating Engineer, September, 1909.

light for human use, taking into account both color and energy-light relationship, would be a light similar to the firefly light containing no radiation beyond the visible spectrum, but differing from it by being white.

II. A FLUORESCENT SUBSTANCE FROM THE FIREFLY.

It was observed by one of us (Coblentz) that the milky fluid which exudes from the firefly (Photinus pyralis) on the slightest touch contains a substance which emits a deep blue fluorescence when the solution is concentrated and free from albuminous matter. In the impure dilute solution the fluorescence is not unlike ordinary kerosene, only very much fainter. This fluorescent substance exists in all parts of the body, the least being present in the head and prothorax, the abdomen (light emitting segments) containing a greater amount, while the thorax and wing covers (which are rather soft) contain the most. The wing covers are bordered with a transparent yellowish-brown margin in which the white fluid, containing the fluorescent substance, is found in the greatest abundance. The fluid exudes in a large drop from the margin of the wing on slight pressure, which fact was taken advantage of in collecting a sample of the pure material. Exposed to the air, the white fluid thickens into a sticky mass, insoluble in ether and alcohol, but soluble in water when fresh. The fluorescent substance is soluble in these liquids, and, in the later experiments was extracted from the insect by means of ether. To this extract water was added, the albuminous matter was precipitated with lead acetate, and the solution was concentrated by boiling. The solution was then neutralized with potassium oxilate to prevent turbidity while photographing the fluorescence spectrum, which was obtained with the same apparatus and photographic plates used in photographing the light emitted by the firefly. The cadmium spark seemed to produce a greater fluorescence than magnesium or aluminum and was used as an exciting source. The absorption appears to be very great, as indicated by the fact that the fluorescence extends but a few millimeters into the solution. The fluorescence spectrum is shown in Fig. 6, and is marked for its intensity and extent. The spectrum shows no structure, and seems to be of the same nature as are the common banded spectra of solutions and of solids.

Substances showing fluorescence are rather common (see Kayser's Spectroscopie, Vol. 4), and the present data are too meager for discussion. The isolation of the fluorescent constituent is a chemical problem.

The life of this insect is less than two months, and further experiments must be deferred. Other species must also be examined to learn whether this is a common constituent of fireflies.[8] There are, perhaps, 25 species of fireflies in this country, while the number of various animals emitting light is very great. Certain light-emitting animals are said to contain a phosphorescent constituent, but no record of a fluorescent constituent has come to the writer's notice. While it possibly has no significance, it seems rather remarkable that a highly fluorescent body fluid should be accidentally present in this light-giving insect, the two spectra being complementary, and the emitted light being of longer wave length than the fluorescent light. The range of the fluorescence spectrum extends from 0.38μ to 0.51μ ($\triangle\lambda = 0.13\mu$ about) while the emitted light extends from 0.51μ to 0.67μ ($\triangle\lambda = 0.16\mu$ about). The maximum of the fluorescence spectrum occurs at about 0.41μ, the plate having a region of maximum sensitivity at 0.43μ, which shifts the maximum of the fluorescence spectrum toward the long wave lengths.

At first there seemed to be no economic reason why fireflies (at least this species) should be burdened with such a large amount of body fluid, especially in the margin of the wing covers. According to Mr. H. Barber, of the National Museum, entomologists are of the opinion that the freely exuded fluid, which has an unpleas-

[8] NOTE.—Since the completion of this paper Coblentz has found that this fluorescent substance occurs in a nonluminous genus (Ellychnia corrusca, Linn.) of the family of true fireflies. Through the courtesy of the U. S. National Museum an opportunity was given him to examine several species of elaters (Pyrophorus noctilucus, etc.) from Cuba and Guatemala which emit a yellow-green light. In all cases the outer horny covering of the insect, the chitinous layer, was found to be perfectly transparent in the regions covering the luminous spots, while elsewhere the integument was a deep reddish brown. From this it is evident that the color of the emitted light is not due to absorption in passing through the chitinous layer, and that it is the sum total of all the light produced. That the red light, said to be emitted by some insects, is the result of absorption seems highly improbable; for it would be poor economy to produce light covering a wide range of the spectrum and then absorb all but the part emitted, whether the emitted part be red, green, or blue.

ant odor and taste, is present simply as a protection against bats and other insectivorous animals. In view of the fact that an insect, which is as conspicuous as is the firefly, would be an easy prey without some protective device, such as an ill-tasting body fluid, this is not an unreasonable explanation.

SUMMARY.

The spectrum of the firefly "Photinus Pyralis" has been photographed on plates sensitive to the whole visible spectrum.

The spectrophotometric curve of the firefly, as compared with a carbon glowlamp, has been obtained by comparison of the photographic densities of the negatives of the firefly and of the glowlamp.

The distribution of radiant energy in the carbon glowlamp has been determined, and by means of the spectrophotemetric relationship the distribution of radiant energy of the firefly derived. The light was found to consist of an unsymmetrical structureless band in the yellow green of the spectrum, with a maximum at 0.57μ, and extending to 0.51μ and 0.67μ.

The luminous efficiency of the firefly is calculated as 96.5 per cent, as compared with 0.4 per cent for the carbon glowlamp, and about 4 per cent for the most efficient artificial illuminant. This value is obtained on the assumption that there is no infra-red radiation, other than that due to the natural body heat, as Langley had concluded from his bolometric study of the Cuban genus. There are reasons for believing that the light emitted is due to a physiological-chemical reaction, not necessarily accompanied by heat waves of low frequency such as occur in a purely thermal (low temperature) radiation. But even if heat waves of low frequency are generated in the photogenic cells, they could not pass out into space on account of the opacity of the outer integument, the chitinous layer, of the insect, which probably can transmit radiation to wave lengths as great as 1.5μ. Now, from our present knowledge of emission and absorption, and from the fact that the emission band in the visible spectrum stops abruptly at 0.7μ, it appears highly improbable that there is appreciable radiation between 0.7 and 1.5μ, hence our assumption of no infra-red radiation can not lead us far astray. Nevertheless, by the exami-

nation of this region of the spectrum, by photographing the undispersed light of the firefly, after it has passed through red glass, as indicated by one of us elsewhere, it is hoped to obtain a qualitative test of this question. It should be noted that we have found the *radiant efficiency,* which is apparently very high. Whether the processes of physiological chemistry, which are probably involved in this light production, are equally efficient is an entirely different question.

WASHINGTON, August 1, 1909.